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Ithaca, NY 14850 -2820

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14. ABSTRACT
This is the final report for the ARO/MURI program "Electrical Control of Magnetic Dynamics in Hybrid Metal-Semiconductor Systems," W911NF-08-2-0032. It describes the main accomplishments of the MURI.

15. SUBJECT TERMS
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Final Report: Electrical Control of Magnetic Dynamics in Hybrid Metal-Semiconductor Systems

ABSTRACT

This is the final report for the ARO/MURI program "Electrical Control of Magnetic Dynamics in Hybrid Metal-Semiconductor Systems," W911NF-08-2-0032. It describes the main accomplishments of the MURI.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

<u>Received</u> <u>Paper</u>

07/25/2014 43.00 P. Braganca, V. Pribiag, D. Ralph, R. Buhrman, O. Lee. Quasilinear spin-torque nano-oscillator via enhanced negative feedback of power fluctuations,
Physical Review B, (12 2013): 0. doi: 10.1103/PhysRevB.88.224411

07/25/2014 49.00 Daniel Schick, Marc Herzog, Haidan Wen, Pice Chen, Carolina Adamo, Peter Gaal, Darrell G. Schlom, Paul G. Evans, Yuelin Li, Matias Bargheer. Localized Excited Charge Carriers Generate Ultrafast Inhomogeneous Strain in the Multiferroic <math xmlns="http://www.w3.org/1998/Math/MathML" display="inline"
><mrow><msub><mrow><mi>BiFeO</mi></mrow><mrow><mn>3</mn></mrow></msub></mrow></math>,
Physical Review Letters, (3 2014): 0. doi: 10.1103/PhysRevLett.112.097602

07/25/2014 48.00 Linze Li, Peng Gao, Christopher T. Nelson, Jacob R. Jokisaari, Yi Zhang, Sung-Joo Kim, Alexander Melville, Carolina Adamo, Darrell G. Schlom, Xiaoqing Pan. Atomic Scale Structure Changes Induced by Charged Domain Walls in Ferroelectric Materials,
Nano Letters, (11 2013): 0. doi: 10.1021/nl402651r

07/25/2014 47.00 J. T. Heron, D. G. Schlom, R. Ramesh. Electric field control of magnetism using BiFeO3-based heterostructures,
APPLIED PHYSICS REVIEWS, (06 2014): 0. doi: 10.1063/1.4870957

07/25/2014 46.00 Christian M. Schlepu?tz, Carolina Adamo, Darrell G. Schlom, Roy Clarke, Yongsoo Yang. Untilting BiFeO3: The influence of substrate boundary conditions in ultra-thin BiFeO3 on SrTiO3,
APL Materials, (2013): 0. doi: 10.1063/1.4827596

07/25/2014 45.00 M. H. Fischer, A. Vaezi, A. Manchon, E.-A. Kim, N. Samarth, D. C. Ralph, A. R. Mellnik, J. S. Lee, A. Richardella, J. L. Grab, P. J. Mintun. Spin-transfer torque generated by a topological insulator,
Nature, (7 2014): 0. doi: 10.1038/nature13534

07/25/2014 44.00 L. Q. Liu, C. F. Pai, Y. Li, O. J. Lee, H. W. Tseng, P. G. Gowtham, J. P. Park, D. C. Ralph, R. A. Buhrman. Central role of domain wall depinning for perpendicular magnetization switching driven by spin torque from the spin Hall effect,
Physical Review B, (1 2014): 0. doi: 10.1103/PhysRevB.89.024418

08/29/2012 12.00 T. van der Sar, Z. H. Wang, M. S. Blok, H. Bernien, T. H. Taminiau, D. M. Toyli, D. A. Lidar, D. D. Awschalom, R. Hanson, V. V. Dobrovitski. Decoherence-protected quantum gates for a hybrid solid-state spin register,
Nature, (04 2012): 0. doi: 10.1038/nature10900

08/29/2012 26.00 R. Buhrman, Luqiao Liu, O. Lee, T. Gudmundsen, D. Ralph. Current-Induced Switching of Perpendicularly Magnetized Magnetic Layers Using Spin Torque from the Spin Hall Effect,
Physical Review Letters, (8 2012): 0. doi: 10.1103/PhysRevLett.109.096602

08/29/2012 25.00 Takahiro Moriyama, Giovanni Finocchio, Mario Carpentieri, Bruno Azzerboni, Daniel Ralph, Robert Buhrman. Phase locking and frequency doubling in spin-transfer-torque oscillators with two coupled free layers,
Physical Review B, (08 2012): 0. doi: 10.1103/PhysRevB.86.060411

08/29/2012 24.00 Lin Xue, Chen Wang, Yong-Tao Cui, J. A. Katine, R. A. Buhrman, D. C. Ralph. Network analyzer measurements of spin transfer torques in magnetic tunnel junctions,
Applied Physics Letters, (2012): 0. doi: 10.1063/1.4737017

08/29/2012 23.00 L. Liu, C.-F. Pai, Y. Li, H. W. Tseng, D. C. Ralph, R. A. Buhrman. Spin-Torque Switching with the Giant Spin Hall Effect of Tantalum,
Science, (05 2012): 0. doi: 10.1126/science.1218197

08/29/2012 22.00 Lin Xue, Chen Wang, Yong-Tao Cui, Luqiao Liu, A. Swander, J. Sun, R. Buhrman, D. Ralph. Resonance Measurement of Nonlocal Spin Torque in a Three-Terminal Magnetic Device,
Physical Review Letters, (04 2012): 0. doi: 10.1103/PhysRevLett.108.147201

08/29/2012 21.00 Joseph Desmarais, Jon F. Ihlefeld, Tassilo Heeg, Ju?rgen Schubert, Darrell G. Schlom, Bryan D. Huey. Mapping and statistics of ferroelectric domain boundary angles and types,
Applied Physics Letters, (2011): 0. doi: 10.1063/1.3643155

08/29/2012 20.00 Michael B. Katz, George W. Graham, Yingwen Duan, Hong Liu, Carolina Adamo, Darrell G. Schlom, Xiaoqing Pan. Self-Regeneration of Pd–LaFeO,
Journal of the American Chemical Society, (11 2011): 0. doi: 10.1021/ja2082284

08/29/2012 19.00 Peng Gao, Christopher T. Nelson, Jacob R. Jokisaari, Seung-Hyub Baek, Chung Wung Bark, Yi Zhang, Enge Wang, Darrell G. Schlom, Chang-Beom Eom, Xiaoqing Pan. Revealing the role of defects in ferroelectric switching with atomic resolution,
Nature Communications, (12 2011): 0. doi: 10.1038/ncomms1600

08/29/2012 18.00 C. T. Nelson, P. Gao, J. R. Jokisaari, C. Heikes, C. Adamo, A. Melville, S.-H. Baek, C. M. Folkman, B. Winchester, Y. Gu, Y. Liu, K. Zhang, E. Wang, J. Li, L.-Q. Chen, C.-B. Eom, D. G. Schlom, X. Pan. Domain Dynamics During Ferroelectric Switching,
Science, (11 2011): 0. doi: 10.1126/science.1206980

08/29/2012 17.00 J. Heron, M. Trassin, K. Ashraf, M. Gajek, Q. He, S. Yang, D. Nikonov, Y-H. Chu, S. Salahuddin, R. Ramesh. Electric-Field-Induced Magnetization Reversal in a Ferromagnet-Multiferroic Heterostructure,
Physical Review Letters, (11 2011): 0. doi: 10.1103/PhysRevLett.107.217202

08/29/2012 16.00 Yong Wang, L. Sham. Quantum dynamics of a nanomagnet driven by spin-polarized current,
Physical Review B, (03 2012): 0. doi: 10.1103/PhysRevB.85.092403

08/29/2012 15.00 D. Toyli, D. Christle, A. Alkauskas, B. Buckley, C. Van de Walle, D. Awschalom. Measurement and Control of Single Nitrogen-Vacancy Center Spins above 600 K,
Physical Review X, (07 2012): 0. doi: 10.1103/PhysRevX.2.031001

08/29/2012 14.00 G. Fuchs, A. Falk, V. Dobrovitski, D. Awschalom. Spin Coherence during Optical Excitation of a Single Nitrogen-Vacancy Center in Diamond,
Physical Review Letters, (04 2012): 0. doi: 10.1103/PhysRevLett.108.157602

08/29/2012 13.00 L. Bassett, F. Heremans, C. Yale, B. Buckley, D. Awschalom. Electrical Tuning of Single Nitrogen-Vacancy Center Optical Transitions Enhanced by Photoinduced Fields,
Physical Review Letters, (12 2011): 0. doi: 10.1103/PhysRevLett.107.266403

08/30/2011 1.00 G. Burkard, P. V. Klimov, D. D. Awschalom, G. D. Fuchs. A quantum memory intrinsic to single nitrogen–vacancy centres in diamond,
Nature Physics, (6 2011): 0. doi: 10.1038/nphys2026

08/30/2011 11.00 Lin Xue, Chen Wang, Yong-Tao Cui, J. A. Katine, R. A. Buhrman, D. C. Ralph. Conditions for microwave amplification due to spin-torque dynamics in magnetic tunnel junctions,
Applied Physics Letters, (7 2011): 0. doi: 10.1063/1.3606550

08/30/2011 10.00 Yong-Tao Cui, Jordan A. Katine, Robert A. Buhrman, Chen Wang, Daniel C. Ralph. Time-resolved measurement of spin-transfer-driven ferromagnetic resonance and spin torque in magnetic tunnel junctions,
Nature Physics, (2 2011): 0. doi: 10.1038/nphys1928

08/30/2011 9.00 Christopher T. Nelson, Benjamin Winchester, Yi Zhang, Sung-Joo Kim, Alexander Melville, Carolina Adamo, Chad M. Folkman, Seung-Hyub Baek, Chang-Beom Eom, Darrell G. Schlom, Long-Qing Chen, Xiaoqing Pan. Spontaneous Vortex Nanodomain Arrays at Ferroelectric Heterointerfaces,
Nano Letters, (02 2011): 0. doi: 10.1021/nl1041808

08/30/2011 8.00 X. Yu, V. Pribiag, Y. Acremann, A. Tulapurkar, T. Tyliszczak, K. Chou, B. Bräuer, Z.-P. Li, O. Lee, P. Gowtham, D. Ralph, R. Buhrman, J. Stöhr. Images of a Spin-Torque-Driven Magnetic Nano-Oscillator,
Physical Review Letters, (4 2011): 0. doi: 10.1103/PhysRevLett.106.167202

08/30/2011 7.00 Pinshane Y. Huang, Carlos S. Ruiz-Vargas, Arend M. van der Zande, William S. Whitney, Mark P. Levendorf, Joshua W. Kevek, Shivank Garg, Jonathan S. Alden, Caleb J. Hustedt, Ye Zhu, Jiwoong Park, Paul L. McEuen, David A. Muller. Grains and grain boundaries in single-layer graphene atomic patchwork quilts,
Nature, (1 2011): 0. doi: 10.1038/nature09718

08/30/2011 5.00 Takahiro Moriyama, Theodore J. Gudmundsen, Pinshane Y. Huang, Luqiao Liu, David A. Muller, Daniel C. Ralph, Robert A. Buhrman. Tunnel magnetoresistance and spin torque switching in MgO-based magnetic tunnel junctions with a Co/Ni multilayer electrode,
Applied Physics Letters, (8 2010): 0. doi: 10.1063/1.3481798

08/30/2011 6.00 Luqiao Liu, Takahiro Moriyama, D. Ralph, R. Buhrman. Spin-Torque Ferromagnetic Resonance Induced by the Spin Hall Effect,
Physical Review Letters, (1 2011): 0. doi: 10.1103/PhysRevLett.106.036601

08/30/2011 4.00 F. J. Heremans, C. D. Weis, T. Schenkel, D. D. Awschalom, G. D. Fuchs, V. V. Dobrovitski, D. M. Toyli. Excited-state spin coherence of a single nitrogen–vacancy centre in diamond,
Nature Physics, (7 2010): 0. doi: 10.1038/nphys1716

08/30/2011 3.00 B. B. Buckley, G. D. Fuchs, L. C. Bassett, D. D. Awschalom. Spin-Light Coherence for Single-Spin Measurement and Control in Diamond,
Science, (10 2010): 0. doi: 10.1126/science.1196436

08/30/2011 2.00 W. F. Koehl, J. B. Varley, A. Janotti, B. B. Buckley, C. G. Van de Walle, D. D. Awschalom, J. R. Weber. Defects in SiC for quantum computing,
Journal of Applied Physics, (05 2011): 0. doi: 10.1063/1.3578264

08/31/2013 27.00 B. B. Buckley, D. J. Christle, C. G. Yale, G. Burkard, F. J. Heremans, L. C. Bassett, D. D. Awschalom. All-optical control of a solid-state spin using coherent dark states,
Proceedings of the National Academy of Sciences, (04 2013): 0. doi: 10.1073/pnas.1305920110

08/31/2013 28.00 Abram L. Falk, Bob B. Buckley, Greg Calusine, William F. Koehl, Viatcheslav V. Dobrovitski, Alberto Politi, Christian A. Zorman, Philip X.-L. Feng, David D. Awschalom. Polytype control of spin qubits in silicon carbide,
Nature Communications, (5 2013): 0. doi: 10.1038/ncomms2854

08/31/2013 29.00 Luqiao Liu, Chi-Feng Pai, D. C. Ralph, R. A. Buhrman. Magnetic Oscillations Driven by the Spin Hall Effect in 3-Terminal Magnetic Tunnel Junction Devices,
Physical Review Letters, (10 2012): 0. doi: 10.1103/PhysRevLett.109.186602

08/31/2013 30.00 Chi-Feng Pai, Luqiao Liu, Y. Li, H. W. Tseng, D. C. Ralph, R. A. Buhrman. Spin transfer torque devices utilizing the giant spin Hall effect of tungsten,
Applied Physics Letters, (2012): 0. doi: 10.1063/1.4753947

08/31/2013 31.00 P. M. Braganca, O. J. Lee, O. Ozatay, L. Liu, G. Finocchio, D. C. Ralph, R. A. Buhrman. Coherent and incoherent spin torque oscillations in a nanopillar magnetic spin-valve,
Applied Physics Letters, (2013): 0. doi: 10.1063/1.4812299

08/31/2013 32.00 J. C. Yang, Q. He, S. J. Suresha, C. Y. Kuo, C. Y. Peng, R. C. Haislmaier, M. A. Motyka, G. Sheng, C. Adamo, H. J. Lin, Z. Hu, L. Chang, L. H. Tjeng, E. Arenholz, N. J. Podraza, M. Bernhagen, R. Uecker, D. G. Schlom, V. Gopalan, L. Q. Chen, C. T. Chen, R. Ramesh, Y. H. Chu. Orthorhombic BiFeO_{3},
Physical Review Letters, (12 2012): 0. doi: 10.1103/PhysRevLett.109.247606

08/31/2013 33.00 Haidan Wen, Pice Chen, Margaret P. Cosgriff, Donald A. Walko, June Hyuk Lee, Carolina Adamo, Richard D. Schaller, Jon F. Ihlefeld, Eric M. Dufresne, Darrell G. Schlom, Paul G. Evans, John W. Freeland, Yuelin Li. Electronic Origin of Ultrafast Photoinduced Strain in BiFeO_{3},
Physical Review Letters, (1 2013): 0. doi: 10.1103/PhysRevLett.110.037601

08/31/2013 34.00 Patrick E. Hopkins, Carolina Adamo, Linghan Ye, Bryan D. Huey, Stephen R. Lee, Darrell G. Schlom, Jon F. Ihlefeld. Effects of coherent ferroelastic domain walls on the thermal conductivity and Kapitza conductance in bismuth ferrite,
Applied Physics Letters, (2013): 0. doi: 10.1063/1.4798497

08/31/2013 35.00 Ryan C. Haislmaier, Nikolas J. Podraza, Sava Denev, Alex Melville, Darrell G. Schlom, Venkatraman Gopalan. Large nonlinear optical coefficients in pseudo-tetragonal BiFeO3 thin films,
Applied Physics Letters, (2013): 0. doi: 10.1063/1.4812978

08/31/2013 36.00 Yi Wang, Chris Nelson, Alexander Melville, Benjamin Winchester, Shunli Shang, Zi-Kui Liu, Darrell G. Schlom, Xiaoqing Pan, Long-Qing Chen. BiFeO_{3} Domain Wall Energies and Structures: A Combined Experimental and Density Functional Theory+U Study,
Physical Review Letters, (6 2013): 0. doi: 10.1103/PhysRevLett.110.267601

08/31/2013 37.00 Yong Wang, L. J. Sham. Quantum approach of mesoscopic magnet dynamics with spin transfer torque,
Physical Review B, (5 2013): 0. doi: 10.1103/PhysRevB.87.174433

08/31/2013 38.00 Tiamhock Tay, L. J. Sham. Theory of atomistic simulation of spin-transfer torque in nanomagnets,
Physical Review B, (5 2013): 0. doi: 10.1103/PhysRevB.87.174407

08/31/2013 39.00 Hongxue Liu, Ryan Comes, Yonghang Pei, Jiwei Lu, Stuart A. Wolf. Structural, magnetic, and nanoscale switching properties of BiFeO3 thin films grown by pulsed electron deposition,
Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures, (2013): 0. doi: 10.1116/1.4802924

08/31/2013 40.00 Ryan Comes, Man Gu, Mikhail Khokhlov, Hongxue Liu, Jiwei Lu, Stuart A. Wolf. Electron molecular beam epitaxy: Layer-by-layer growth of complex oxides via pulsed electron-beam deposition,
Journal of Applied Physics, (2013): 0. doi: 10.1063/1.4774238

08/31/2013 41.00 Ryan Comes, Mikhail Khokhlov, Hongxue Liu, Jiwei Lu, Stuart A. Wolf. Magnetic anisotropy in composite CoFe2O4-BiFeO3 ultrathin films grown by pulsed-electron deposition,
Journal of Applied Physics, (2012): 0. doi: 10.1063/1.3676413

08/31/2013 42.00 Ryan Comes, Hongxue Liu, Mikhail Khokhlov, Richard Kasica, Jiwei Lu, Stuart A. Wolf. Directed Self-Assembly of Epitaxial CoFe,
Nano Letters, (05 2012): 0. doi: 10.1021/nl3003396

TOTAL: **49**

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals: 8

(c) Presentations

1. D.D. Awschalom, Gordon Research Conference on Quantum Science, Easton, MA, July 27-August 1, 2014.
2. D.D. Awschalom, "Quantum Spintronics," Eighth International Conference on the Physics & Applications of Spin Phenomena in Solids (PASPS VIII), Washington DC, July 28-31, 2014.
3. D.D. Awschalom, "Quantum spintronics: Engineering and manipulating atom-like spins in semiconductors," CIMTEC 6th Forum on New Materials, Conference on Mass, Charge and Spin Transport in Materials, Florence, Italy, June 16-20, 2014.
4. D.D. Awschalom, "Beyond electronics: abandoning perfection for quantum technologies," Fourth International Center for Quantum Materials Workshop on Spintronics, International Center for Quantum Design, Materials and Structures, Peking University, Beijing, China, June 2-4, 2014.
5. D.D. Awschalom, Plenary Speaker, "Quantum Spintronics", New Diamond and Nano Carbons (NDNC) Conference, Chicago, IL, May 25-29, 2014.
6. D.D. Awschalom, Hans Bethe Lectures, Cornell University, Ithaca, NY, April 7-11, 2014. "Beyond Electronics: Abandoning Perfection for Quantum Technologies", Physics Colloquium, April 7, 2014; "Ultrafast quantum control of single electron orbital and spin dynamics in diamond", Physics Seminar, April 8, 2014; "Engaging Diamonds in the Quantum Age", Public Lecture, April 9, 2014.
7. D.D. Awschalom, Marker Lectures, Pennsylvania State University, University Park, PA, March 26-28, 2014. "Engaging Diamonds in the Quantum Age", Public Lecture, March 26, 2014; "Beyond Electronics: Abandoning Perfection for Quantum Technologies", Physics Colloquium, March 27, 2014; "Ultrafast quantum control of single electron orbital and spin dynamics in diamond", Physics Seminar, March 28, 2014.
8. D.D. Awschalom, "Quantum spintronics", The International Meeting on Spintronics for Integrated Circuit Application and Beyond, Tokyo, Japan, March 13, 2014.
9. D.D. Awschalom, "Mobile electron spin resonance with spins in optically-trapped nanodiamonds", Symposium on Exploring the Foundations of Magnetism with New Nanoscale Probes, Annual Meeting of the American Association for the Advancement of Science, Chicago, IL, February 13-17, 2014.
10. D.D. Awschalom, "Ultrafast quantum control of single electron orbital and spin dynamics in diamond",International Symposium on Topological Quantum Technology, University of Tokyo, Tokyo, Japan, January 27-30, 2014.
11. D.D. Awschalom, "Beyond electronics: abandoning perfection for quantum technologies", Physics Colloquium, University of Chicago, Chicago, IL, January 16, 2014.
12. D.D. Awschalom, "Beyond electronics: abandoning perfection for quantum technologies", Goteborg Mesoscopic Lecture, Royal Swedish Academy of Sciences & Nobel Institutes of Physics, Chalmers University, Goteborg, Sweden, December 6, 2013.
13. D.D. Awschalom, Experimentalist of the Week, "Abandoning perfection: quantum control of defects for sensing and information processing", KITP Program on Spintronics: Progress in Theory, Materials, and Devices, Kavli Institute for Theoretical Physics, Santa Barbara, CA, November 18-22, 2013.
14. D.D. Awschalom, "Beyond electronics: abandoning perfection for quantum technologies", Physics Colloquim, Northwestern University, Evanston, IL, November 18, 2013
15. D.D. Awschalom (and A. Falk), "Engineering single spins in semconductors for sensing and computation", 60th Annual AVS International Symposium and Exhibition, Long Beach, CA, October 27-November 1, 2013.
16. D.D. Awschalom, "Beyond electronics: abandoning perfection for quantum technologies", Materials Science Special Colloquium, Argonne National Laboratory, Illinois, October 3, 2013
17. D.D. Awschalom, D.D. Awschalom, "Quantum control of single spins in semiconductors for sensing and information processing", Ultrafast Magnetism Conference, Strasbourg, France, October 28-November 1, 2013.
18. D.D. Awschalom (and A. Falk), "Spin manipulation in SiC", International Conference on Silicon Carbide and Related Materials (ICSCRM 2013), Miyazaki, Japan, September 29-October 4, 2013.
19. D.D. Awschalom, "Beyond electronics: abandoning perfection for quantum technologies", Munich Center for NanoScience Workshop on Nanosciences: Great Adventures on Small Scales, Venice International University, Venice, Italy, September 16-20, 2013.
20. R. A. Buhrman, "Spin Hall effects, spin torque and interfacial spin-orbit phenomena in ferromagnetic/normal metal nanostructures," Samsung Electronics STT-MRAM Global Innovation Forum, 2013, Milpitas CA, Invited, July 13, 2013.
21. R. A. Buhrman, "Spin Hall effects, spin torque and interfacial spin-orbit phenomena in ferromagnetic/normal metal nanostructures," Kavli Institute for Theoretical Physics Spintronics 13 Workshop, Santa Barbara, CA, Invited, Sept. 30, 2013.
22. R. A. Buhrman, "Spin Hall effects, spin torque and interfacial spin-orbit phenomena in ferromagnetic/normal metal nanostructures", Materials Research Society Fall Meeting 2013 Symposium U, Boston MA, Invited, Dec. 1-6, 2013.
23. R. A. Buhrman, "Spin Hall effect and spin torques in ferromagnet/normal metal nanostructures," 8th International Conference on Advanced Materials and Devices (ICAMD 2013), Jeju South Korea, Invited, Dec. 11-13, 2014.
24. R. A. Buhrman, "The Spin Hall Effect, Spin Currents and Spin Orbit Torques in Ferromagnetic-Normal Metal Nanostructures," American Physical Society Meeting, Denver, Co, Invited, March 3 – 7, 2014.
25. R. A. Buhrman, "The Spin Hall Effect, Spin Currents and Spin Orbit Torques in Ferromagnetic-Normal Metal Nanostructures," German Physical Society Meeting, Dresden, Germany, Invited, March 33 – April 4, 2014.
26. D. C. Ralph, "Manipulating Magnetic Devices Using Spin Transfer Torque from the Giant Spin Hall Effect," Seventh International School and Conference on Spintronics and Quantum Information Technology (Spintech VII), July 29 – Aug. 2, 2013, Chicago, IL
27. D. C. Ralph, "Spintronics Research at Cornell (with some questions for you)," Experimentalist of the week at the KITP program "Spintronics: Progress in Theory, Materials, and Devices," Oct. 14-18, 2013, Santa Barbara, CA

Number of Presentations: 27.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Electrically Gated Three-Terminal Circuits and Devices Based on Spin Hall Torque Effects in Magnetic Nanostructures, R. A. Buhrman, D. C. Ralph, Chi-Feng Pai, and Luqiao Liu, Patent Application PCT/US13/53874, filed 8/6/2013.

Patents Awarded

Awards

D. D. Aschalom, Bethe Lecturer, Cornell University (2014)
D. D. Aschalom, Marker Lecturer, Pennsylvania State University (2014)
D. D. Aschalom, Nobel Week Dialogue Panelist, Sweden (2013)
D. D. Aschalom, Gothenburg Mesoscopic Lecturer, Chalmers, Nobel Institutes of Physics, Sweden (2013)
D. D. Aschalom, Slichter Lecturer, University of Illinois (2013)
D. D. Aschalom, Elected, European Academy of Sciences (2013)

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Jonathan Gibbons	1.00	
Will Koehl	1.00	
Christopher Yale	1.00	
Praveen Gowtham	1.00	
Yun Li	0.10	
Yonghang Pei	1.00	
FTE Equivalent:	**5.10**	
Total Number:	**6**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
L. C. Bassett	1.00
C. Adamo	0.50
Luis Vilela Leao	0.50
J. T. Heron	0.10
FTE Equivalent:	**2.10**
Total Number:	**4**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Jiwei Lu	0.10	
FTE Equivalent:	**0.10**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED	Discipline
Hope Bretscher	1.00	physics
FTE Equivalent:	**1.00**	
Total Number:	**1**	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

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Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME	
Ryan Comes	
Yun Li	
Total Number:	**2**

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

See attachment.

Technology Transfer

Final Report, ARO/MURI, W911NF-08-2-0032

Electrical Control of Magnetic Dynamics in Hybrid Metal-Semiconductor Systems

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For this final report, the program manager Dr. John Prater has requested that we identify the main accomplishments of the MURI and indicate how this MURI has moved the field as a whole forward. Therefore this report will not describe all of the research performed by the MURI, but will focus briefly on four main areas of accomplishments:

1. Efficient manipulation of magnetic devices using spin torque from the spin Hall effect.
2. Spin transfer torque from a topological insulator.
3. Voltage-driven magnetic reversal using multiferroic $BiFeO_3$.
4. Electrical and optical control of single spins in diamond and new quantum materials

I. Efficient manipulation of magnetic devices using spin torque from the spin Hall effect

When this MURI began in 2008, the most efficient mechanism known for the electrical manipulation of magnetic devices was spin-transfer torque from a spin-polarized current. In this mechanism, an unpolarized charge current is converted to a spin-polarized current by passage through a thin magnetic layer or a magnetic tunnel junction so that it undergoes spin filtering, and then this spin-polarized current applies a torque to another magnetic layer downstream by direct transfer of angular momentum. Currently, a long list of companies (e.g., Crocus Technologies, Everspin Technologies, Global Foundries, Hitachi, IBM, Intel, Qualcomm, Samsung, Sony, Spin Transfer Technologies, TDK, Toshiba) are investing in the development of nonvolatile magnetic memories which use spin-transfer torque as the writing mechanism, and in 2013 Everspin Technologies began selling the first commercial products based on this effect.

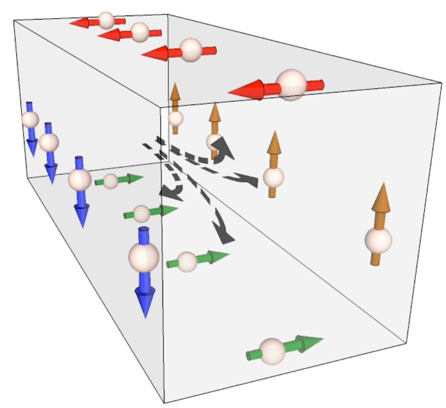


Fig. 1. Illustration of the spin Hall effect in a heavy metal.

Despite its rapid commercial development, the spin transfer torque mechanism has some limitations. Because each electron carries an angular momentum of $\hbar/2$ and transfers this angular momentum at most once to the magnet, the strength of the torque per unit current has an upper limit equal to $\hbar/2$ per unit charge in the current. This limits the potential efficiency of spin torque switching in memory applications and (because the size of the memory element is at present limited by the size of a transistor needed to source the current) it also presents an obstacle for scaling spin torque memories to large densities. One primary accomplishment of this MURI is the discovery that certain heavy metals (W, Ta, Pt) possess a giant spin Hall effect (SHE) (Fig. 1) that can provide much more efficient manipulation of magnetic devices than conventional spin transfer torque, exceeding by a factor of 10 or more the previous limit of $\hbar/2$ angular momentum transferred per electron. The fundamental reason for this improved efficiency is that in spin Hall samples each electron can transfer angular momentum to the ferromagnetic layer many times while traveling through the device (inset in Fig. 2). Also, because the resulting flow of spin current is perpendicular to the charge current, the SHE provides new opportunities for hybrid devices in which spin currents can be injected efficiently into insulating and semiconducting materials without the need to pass large charge current densities through these high-resistivity materials.

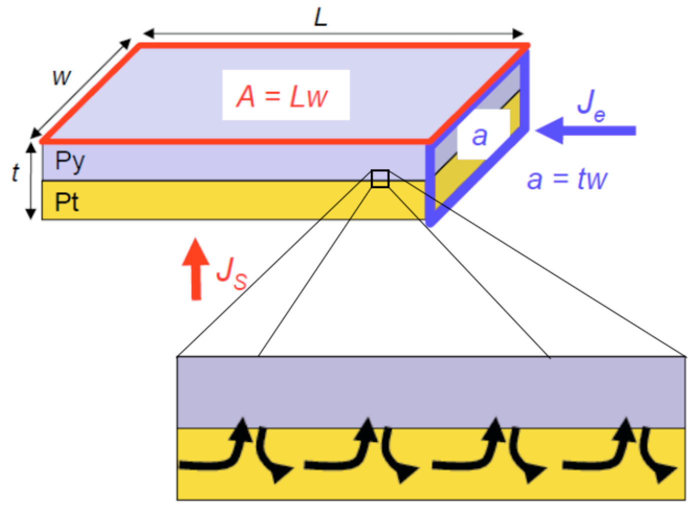


Fig. 2: The charge current J_e and the spin current J_s are perpendicular to each other in the spin Hall effect. High efficiency is possible because each electron transfers spin several times as indicated in the inset.

The MURI's work on the giant spin Hall effect resulted in one *Science* paper,[1] three *Physical Review Letters*,[2-4] one *Applied Physics Letter*,[5] and one *Physical Review B* paper.[6] The MURI's contributions to this field started with the development of improved methods for measuring the strength of the SHE, which showed that most of the previous measurements of the SHE in metals were incorrect — they greatly underestimated the strength of the effect. The MURI was the first to point out that torque from the SHE was more efficient than the upper bound of $\hbar/2$ per unit charge that applies to the conventional spin-transfer torque mechanism.[2] The MURI provided direct demonstrations of this improved efficiency by using the spin-Hall effect to switch magnetic layers with magnetizations oriented both in the sample plane[1,5] and perpendicular to the plane,[1,2] and we pointed[2] out that the giant SHE explained previously-mysterious results from other groups concerning current-driven magnetic domain wall motion. (The switching of perpendicularly-magnetized layers had also been demonstrated by a different research group,[7] but they ascribed the effect to a different mechanism, a Rashba effect in the magnetic layer rather than the spin Hall effect in the heavy metal.) The MURI discovered the two materials that currently have the largest-known spin Hall effects, β-Ta and β-W. These two materials are already used routinely in magnetic device fabrication, which should enable rapid development of commercial magnetic memories based on the SHE. In addition to potential memory applications, the MURI has also demonstrated that the giant spin Hall torque from a direct current can excite steady-state magnetic precession for use in producing magnetic nano-oscillators.[4] These findings have been rapidly reproduced and extended by other researchers. The MURI's May 2012 *Science* paper[1] has already been cited 159 times and two of the *PRL*s[2,3] have been cited 109 and 71 times.

<u>2. Spin transfer torque from a topological insulator</u>

The MURI has very recently discovered that the topological insulator Bi_2Se_3 can be used to generate current-induced spin transfer torques that are another order of magnitude more efficient at room temperature than even the spin Hall torque effects described above, with the results published in *Nature*.[8] This effect can be understood as arising from a locking between the electron wavevector and spin orientation for electrons in surface state of a topological insulator.[9-11] Research performed by Kang Wang's group after learning of our results indicates that the effect can be stronger still at cryogenic temperatures.[12] This discovery of spin torques generated by a topological insulator is very exciting from a fundamental-science point of view. In terms of applications, unlike the torque from the spin Hall effect which can be used straightforwardly with already existing magnetic devices, to take advantage of the intrinsic high efficiency of the topological-insulator spin-torque for practical technologies will require the development of new types of magnetic devices. This is because topological insulator devices must be integrated with insulating ferromagnetic layers (rather than conventional metallic ferromagnets) in order that the applied current is not wasted by being shunted away from the topological insulator through the magnet. The development of magnetic technologies based on topological insulators and insulating ferromagnets represents an important opportunity for future research and development.

3. Voltage-driven magnetic reversal using multiferroic $BiFeO_3$

One of the primary original goals of the MURI was to develop efficient voltage-based (as opposed to current-based) magnetic manipulation schemes based on the room-temperature multiferromic material $BiFeO_3$, with the goal being to eliminate Ohmic losses so as to yield improved energy efficiency for magnetic technologies. The culmination of this line of research has been the demonstration of reproducible 180° reversal of in-plane magnetized domains in ferromagnetic CoFe layers on $BiFeO_3$ by a low-voltage (5-7 V) signal applied in the out-of-plane direction. The paper reporting this result is currently out to reviewers at *Nature*.[13] This work improves upon previous results which showed switching driven by an in-plane electric field, but which required > 100 V, close to the threshold for sample destruction, and was not reliably reproducible. The new out-of-plane field result is somewhat surprising in that if one considers only the force exerted by the electric field then by fundamental symmetry arguments the application of an out-of-plane electric field should not be able to produce full 180° in-plane rotation of individual domains in $BiFeO_3$. The MURI has shown instead that 180° reversal is achieved by a 2-step process that results from both the applied electric field and boundary conditions related to strain within bilayer. The energy consumption per switch per unit area of these magnetoelectric spin-valve devices is 480 μJ/cm^2, roughly an order of magnitude lower than an optimized conventional spin torque device, and comparable to projections for magnetic memories operated by a spin Hall torque. Future work will be aimed at incorporating the multiferroic reversal mechanism into practical device geometries.

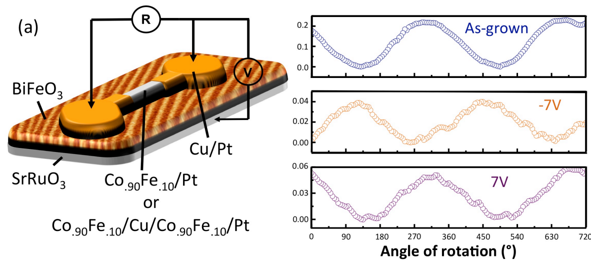
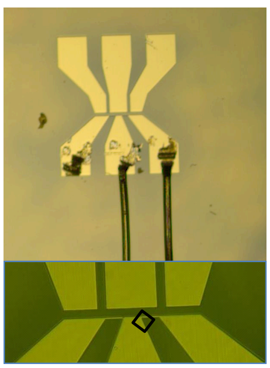


Fig. 3. Schematic of a magnetic devics on $BiFeO_3$ and anomalous magnetoresistance curves demonstrating magnetic reversal by a perpendicular electric field.

4. Electrical and optical control of single spins in diamond and new quantum materials

The MURI has produced several field-leading results related to improving quantum control of single spins in diamond NV centers, to extending the capability to manipulate single spins beyond diamond to other materials, and to developing applications of quantum defects as magnetic-field and temperature sensors. Among other papers, this has resulted in three publications in *Science*,[14-16] one in *Nature*,[17] and two in the *Proceedings of the National Academy of Sciences*.[18,19] The highlights of this research include:

Gigahertz control of a single electron spin at room temperature. We explored the high frequency limits to manipulating a single spin in the solid state. To push resonant microwave control of single NV centers at ambient conditions up to gigahertz rates, we fabricated coplanar waveguides on diamond substrates. These on-chip structures enabled the generation of large oscillating magnetic fields (~500 G) that produce spin rotations on the same timescale as Larmor precession and provide an opportunity to study an unusual regime in spin resonance. Under these conditions reproducible coherent spin flips occur in sub-nanosecond timescales - faster than expected in standard spin resonance. To gain more insight into these dynamics, we performed numerical simulations by using pulses measured from the experiment with no free parameters. The calculations revealed remarkably good qualitative and quantitative agreement with the measurements. Contrary to conventional thinking, this breakdown of the rotating wave approximation provides new opportunities for time-optimal quantum control of a single spin, and demonstrated quantum control in the GHz regime. The results were published in *Science*.[14]



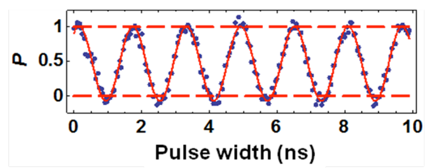


Fig. 4. Co-planar waveguides on diamond chips with 1 micron feature sizes. Data shows 630 MHz Rabi oscillations on a single spin in the box. Circuit operates above 1 GHz.

Density functional theory prediction & discovery of new quantum materials for hybrid systems. Identifying and designing physical systems for use as qubits, the basic units of quantum information, are critical steps in the development of quantum systems for exploring fundamental materials physics, advanced sensing instrumentation, and quantum information processing. Among the possibilities in the solid state, the NV center in diamond stands out for its robustness—its quantum state can be initialized, manipulated, and measured with high fidelity at room temperature. Under the MURI effort we developed a method to systematically identify other deep center defects in different materials with similar quantum-mechanical properties. We presented a list of physical criteria that these centers and their hosts should meet and explained how these requirements can be used in conjunction with electronic structure theory to intelligently sort through candidate defect systems. To illustrate these points in detail, we compared electronic structure calculations of the NV center in diamond with those of several deep centers in 4H silicon carbide (SiC). We then discuss the proposed criteria for similar defects in other tetrahedrally coordinated semiconductors. This work was published in the *Proceedings of the National Academy of Sciences*,[18] and led to the Awschalom group's later discovery of spin qubits in SiC, spin-dipole coupling control, and recently, experimental measurements of single spin coherence in this system with millisecond-scale relaxation times. In addition, the predictions of spin coherence using defects in ZnO have been observed by Professor Greg Fuchs at Cornell.

Electrical tuning of individual electron spins. Two important challenges in creating and controlling single spins are to find new schemes for manipulating individual quantum states in a scalable manner, and to create truly identical quantum states for entanglement. In contrast to employing local magnetic fields, we developed micron-scale devices to manipulate electric fields in three dimensions, to compensate the intrinsic local strain and electrostatic fields of individual NV centers and achieve full electrical control of the orbital Hamiltonian. Furthermore, by analyzing the Stark shifts as a function of applied voltages, we infer a surprising amplification and rectification of the local electric field, consistent with electrostatic contributions from photoionized charge traps within the diamond host. By harnessing this reproducible effect, we can electrically tune the NV-center Hamiltonian to arbitrary points across an extremely large frequency range. By coupling multiple NV centers to indistinguishable photons with this technique, photonic networks could provide a quantum bus to coherently couple distant NV centers, and entanglement swapping protocols could enable long-distance quantum key distribution. The results were published in *Physical Review Letters*.[20] Soon afterwards, this discovery led to the experimental demonstration of quantum entanglement using single spins in diamond separated over a few meters (Delft).

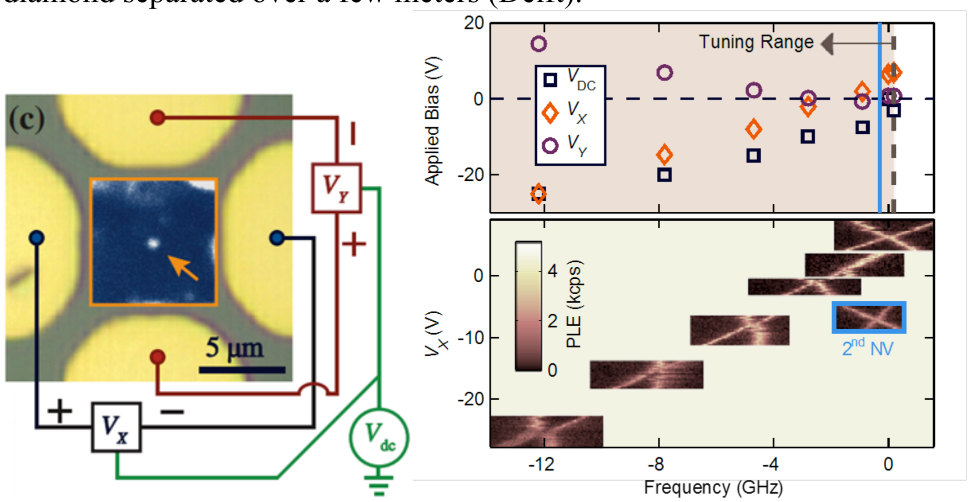


Fig. 5. (left) Four-terminal device enabling local electric field control around a single spin, identified by the PL image. (right) Range of voltage tuning showing ~10 GHz frequency tunability with modest bias to create identical Hamiltonians (PLE images showing anticrossings of spin state).

Demonstration of a single-spin nuclear memory. In addition to having an addressable electronic spin, the NV center in diamond contains a nuclear spin on its nitrogen atom, which is an attractive candidate for a quantum memory due to both a long spin coherence time and its deterministic presence. We investigated coherent swaps between the NV center electronic spin state and the nuclear spin state of nitrogen using Landau-Zener transitions performed outside the asymptotic regime, a technique successfully employed in atomic physics. The swap gates are generated using lithographically fabricated waveguides that we have designed and implemented to form a high-bandwidth, two-axis vector magnet on the diamond substrate. We successfully demonstrated swap times as short as 120 ns with fidelities up to 92±5% at room temperature. These experiments provide tools for coherently manipulating and storing quantum information in a scalable solid-state system at room temperature, and show that a single nuclear spin may be used as a local quantum memory in solid state materials. This research was published in *Nature Physics*.[21]

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